Collaborative robot systems

Design of systems with „Power and Force Limiting“ function

Issue 08/2017 Translation of the German version FB HM-080

Collaborative robot systems can be applied in the „Power and Force Limiting“ function without conventional protective devices such as fences and light curtains. Concerning the requirements of standards, rules and regulations and the implementation of research results, there is a need for practical guidance for manufacturers, system integrators, users, accident insurance Institutions and certification bodies.

Figure 1: “Sign collaborative robot system”

Table of contents

1 Legal regulations and standards

Collaborative robot systems fall within the scope of the EC Machinery Directive 2006/42/EC [1]. For placing them on the market, they have to be provided with an EC Declaration of conformity and a CE mark. Application of the harmonized European standards EN ISO 10218-1 [2] and EN ISO 10218-2 [3] induce the presumption of conformity. It can thus be assumed that the requirements of the EC Machinery Directive are complied with.

The collaborative robot system comprises the collaborative robot(s), tools, workpieces and devices, thereby forming machinery according to the EC Machinery Directive. The individual robot is considered to be partly completed machinery. Partly completed machinery has to be provided with a declaration of incorporation instead of an EC declaration of conformity

Due to this very new technology, the specific requirements for collaborative robot systems are not yet comprehensively described in EN ISO 10218-1 and EN ISO 10218-2. The same applies to DGUV Information 209-074 „industrial robots“ [4].

Within the scope of the technical specification ISO TS 15066 [5], the requirements are currently being further developed. In particular, research results will be included in this technical specification. On completion of ISO TS 15066, its contents will be used for a planned revision of the standards EN ISO 10218-1 and EN ISO 10218-2.

In the meantime and beyond that, this information is intended to support manufacturers, system integrators and certifiers with the development, construction, certification and assessment of safe collaborative robot systems.

2 Risk assessment

The risk assessment is a procedure required by the Machinery Directive. The documentation of the risk assessment has to be available with the machine manufacturer or the integrator at the time of placing onto the market at the latest. The risk assessment procedures for collaborative robot systems do not generally differ from those for other machines or robot systems. Examples of risk assessments are included in [4].

Risk assessments for collaborative robot systems have to consider in particular the immediate proximity of the human and the robot system and derive appropriate protective measures. A comprehensive compilation of possible hazards which have to be taken into account on collaborative robot systems is mentioned in [3] and [5]. Contact situations between the human and the robot system have to be limited to a minimum.

The protective measures to be derived from the risk assessment may be conventional protective measures (e. g. light curtains, laser scanners) but also new types of protective measures (e. g. force limitations, limitations of the range of motions) or a combination of both. The basic requirements are stated in EN ISO 10218-1 and EN ISO 10218-2 as well as in ISO TS 15066 and will be explained in the following.

3 Power and Force Limiting / PFL

Among the types of collaboration according to ISO TS 15066,

- hand guiding
- safety-related stop
- speed and separation monitoring
- power and force limiting

this DGUV-Information does only consider power and force limiting. This function enables a fenceless operation. The robot systems are designed in such a way that in case of a contact e. g. between persons and robot tool, robot parts or the workpiece, biomechanical limit values are not exceeded (force, pressure). The force or pressure application depends among other factors on the following protective measures:

- active technical protective measures in the robot system, e. g. tactile safeguards, torque sensors, force sensors, speed and range limits (see also Figure 4).
- passive protective measures, e. g. elastic grippers, padding, shaping of the robot, the tool, the workpiece and of all other devices involved in the work process.

Robots that are designed for this type of collaboration are also called lightweight robots. However, no safety characteristics can be derived solely from the term.

4 Requirements on robots

The robots intended for use should be designed and selected particularly with regard to the safety functions required in the application. If e. g. no adequate safety-related control functions are provided by the control system, they have to be retrofitted. If necessary, an alternative robot type has to be selected.

Besides the obligatory safety functions stated in EN ISO 10218-1, such as e. g. emergency stop, industrial robots intended for the human-robot collaboration usually have to be provided with the following safety functions in the function power and force limiting:

a) safe monitoring / limitation of torque or force

taking into account the edge geometry of the robot system surfaces which are involved in the work process, it results from the monitoring of force or torque on the robot that also the pressure is monitored at the contact surfaces.

b) safe speed monitoring

in order to ensure e. g. for force and/or torque monitoring, that a stop reaction can take place taking into account the system-related reaction time, normally a safe speed monitoring is necessary.

c) safe position monitoring

in order to be able to define and limit work areas according to the load limits which are assigned to the body regions, (e. g. exclusion of neck and head), normally, a safely monitored position (safe space limits) is required. Depending on the hazard exposure, in addition to the monitoring on the tool, a monitoring of individual axes has to be provided as well.

d) mode selection and enabling switch

according to EN ISO 10218-1, a lockable mode selection switch or equal access guarding (e.g. access code) as well as enabling switches are obligatory safety functions of industrial robots. For collaborative robot systems, an enabling switch may be dispensed with according to ISO TS 15066, if safety limits (e. g. speed, force, range of motion) ensure that all activities, such as servicing, maintenance, repair, setting, programming can be carried out as safely as by the use of an enabling switch. It must not be possible to deselect or change the safety limits such that a hazardous situation arises. Since the safety limits - except robot systems with inherently safe design (miniature robots) - can normally be parameterized, the absence of mode selection switch and enabling switch is normally not possible. On the first putting into service or subsequent modifications by the user (e. g. new parts program), safety limits must be changed. This has to be done by means of an enabling switch.

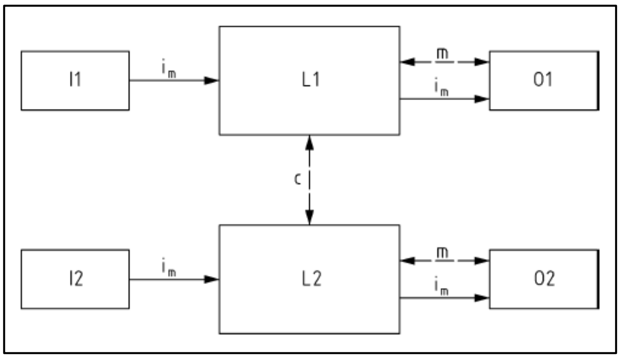


Figure 2: Control architecture according to EN ISO 13849-1 category 3

The safety functions shall meet EN ISO 13849-1 [6] category 3/PLd. In addition, the edges of all robot parts (robot arms, tool holder) should be rounded. Padding enlarges the surfaces and has positive effects. In order to keep contact forces low due to inertia, the loads should be low as well.

5 Robot system (application)

Besides the robot, the robot system also includes the robot tools, the workpieces, the handling system as well as all devices and safeguards involved.

According to the current state of the art, large, angular and heavy workpieces are not suited for this kind of collaboration. The inertia of heavy workpieces normally leads to exceeding the force and pressure limits (see Annex A).

Due to the proximity to the human, the robot movements (paths) intended for collaborative operation are decisive factors. Normally, the robot travel ranges including tool and workpiece have to be limited by means of the system layout and the function „Safe limitation of range of motion” (safe spatial limits), in order to e. g. exclude sensitive body parts such as head and neck from the work area within the scope of the intended use (Figure 4).

Any contact with the head has to be generally excluded by the system layout even in the scope of the foreseeable misuse. If this cannot be fully ensured, such contact situations have to be reduced to a minimum. Measurements of the biomechanical limit values have to be carried out for those contact situations. The sensitive areas at the head or neck (e. g. eyes or larynx), however, must under no circumstances become a point of contact. This can be achieved by design measures, e. g.

- flat contours
- padding
- defensive path design
- turn away edged contours from the operator during travel
- restriction of robot working ranges (TCP and joints)
- shifting of large relative movements far away from sensitive body regions (in case of table applications, e. g. downwards)

If risks persist, these areas have to be excluded from access, e. g. by additional guards (even transparent ones) and provided with complementary instructions to the users (see also section 7).

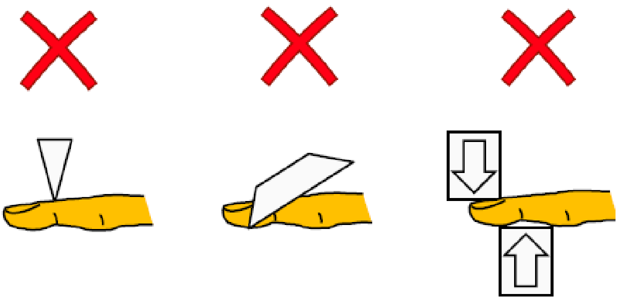


Figure 3: Avoidance of points, sharp edges and shearing edges

For selecting the robot movements (paths) which have to be expected on contact with corresponding body regions, typically the following foreseeable situations should be assumed:

- manual intervention into the work area, intentionally or unintentionally, e. g. reflexively
- observation of the working process, e.g. by leaning into or leaning over
- detection and intervention in case of malfunction
- picking up falling parts
- bumping of the robot arms against the body
- bumping of the tool and the workpiece against the body

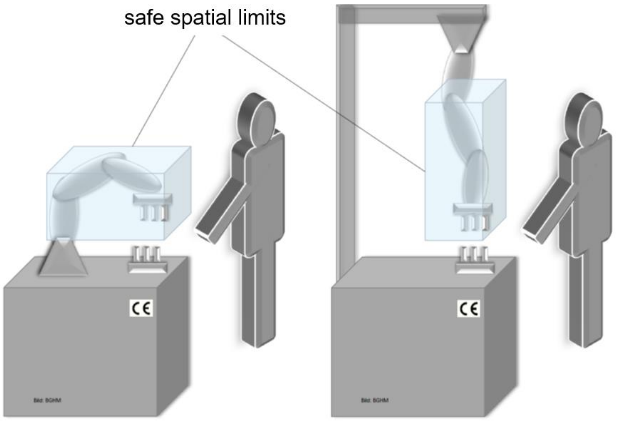


Figure 4: Example of limiting the robot work area by means of safe area limits

Moreover, the safety requirements according to EN ISO 10218-2 apply to the robot system. Particular care must be taken to ensure that emergency stop devices are easily accessible and provided in sufficient number. Resulting from the possible direct contact between a person and the robot system, there shall always be a means available to free oneself when being trapped, e.g. by means of a switching device for releasing the mechanical holding brakes. Contact situations may arise by a clamping incident, e.g. in case of a reflexive intervention into the tool area. Contact situations between human and robot systems have to be generally restricted to a minimum. This applies to contact by bumping and to possible clamping situations. Clamping situations – if they cannot be entirely prevented – should only occur to the upper limbs.

6 Determination of biomechanical loads (force and pressure)

As far as there is no experience available on occurring contact forces and pressures (e. g. simulation tools), the forces and pressures for the contact scenarios which have been selected according to the risk assessment, have to be measured according to table A.2 (see Annex A). On the condition of a well-prepared application design and path planning, the measurements for a typical robot system in the collaborative mode power and force limiting may be reduced to a few selected contact scenarios. The limit values are composed of a limit value for the pressure and a limit value for the force.

The limit value for the pressure considers the influence of the geometry of all machine parts involved in the work process (edges, corners, points). It applies: the smaller the surfaces, i. e. the more sharp-edged, e. g. the tools are, the higher the pressure. The limit values according to Table A.2 or ISO TS 15066 result from the latest research on the determination of pain thresholds [7].

Besides the pressure, the force always needs to be considered as well. This is of particular relevance e. g. for extensive or padded parts of the robot system. On contact with body parts, the measured pressure is thus minimal or insignificant. In this case the force has to be limited, so that despite a soft impact on the body no overloads are applied to the deeper tissue. Furthermore, the operator must not be knocked-over.

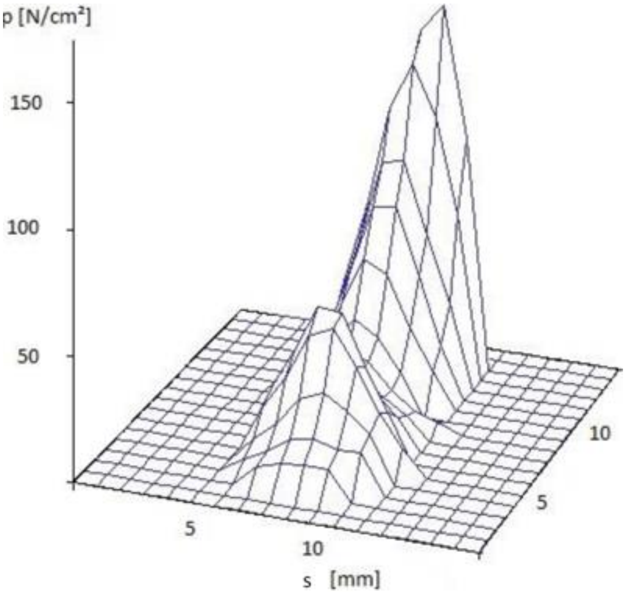


Figure 5: Pressure distribution on an edged contour (example).

As soon as one of the limit values, force or pressure, is exceeded, the requirements are considered to be not fulfilled. Normally, the safety limits for the force which are set at the robot in conjunction with the safely monitored speed have to be reduced. If, e. g. the pressure values continue to be exceeded afterwards, the design has to be modified, e. g. by larger surfaces, padding, elastic grippers etc. .

Limitations of force, speed and similar which are not identified as safety functions must not be considered in the scope of the measurement. The robot system has to offer an option to switch off such functions for programming and measuring purposes or Worst-Case-assumptions have to be taken (maximum possible force, speed, range etc.).

For the body regions selected for the measurement, the damping materials and spring constants indicated in Table 1 may be applied.

Body region	Damping material K1 [Shore A]	Thick-ness [mm]	Spring K2 [N/mm]
Skull and forehead	critical zone		150
Face			75
Hand and finger	70	7	75
Neck			50
Lower arm and wrist			40
Chest			25
Pelvis			25
Lower leg	30	14	60
Thigh and knee			50
Back and shoulders			35
Upper arm and ellbow			30
Abdomen	10	21	10

Table 1: Damping material and spring constants for a measuring setup according to Figure 7

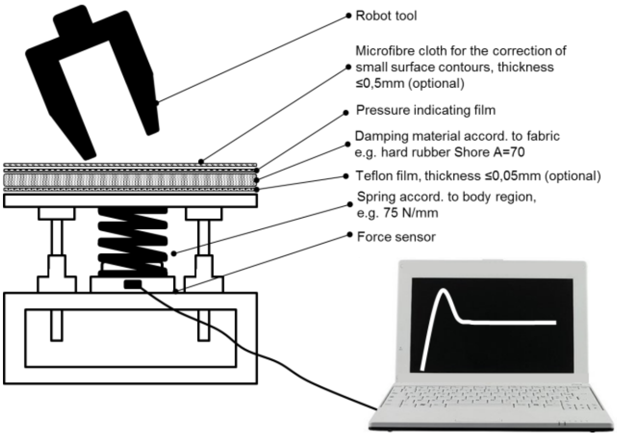


Figure 6: Example of a measuring system for force and pressure

Practical experience showed that the force measurement results deviated only slightly after the diverse springs had been replaced. Provided that head and neck are excluded from the work area of the robot system, it may be sufficient within the intended use and foreseeable misuse to use only the Worst Case (hardest) spring of 75 N/mm. If it should be necessary within the scope of the foreseeable misuse to assess a contact, e.g. in the area of the forehead, a spring of 150 N/mm has to be used.

For the measurement of the biomechanical limit values, a measuring system according to Figure 6 should be applied. The measuring device has to be fixed during the measurement.

The measuring system must either enable simultaneous or subsequent measurements of the force and the pressure for the relevant contact situation. Force and pressure can be measured by a measuring setup according to Figure 6.

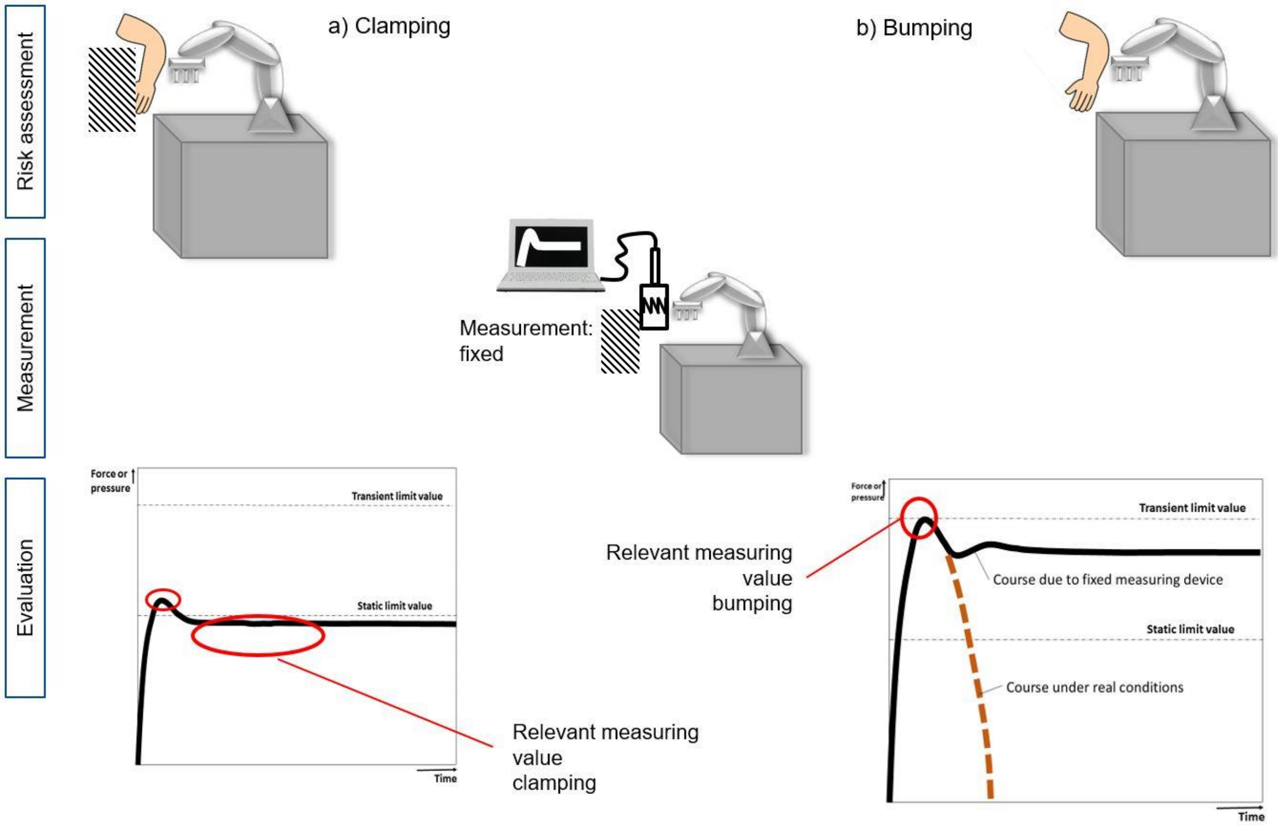


Figure 7: Measurement of pressure or force for clamping and bumping situations

The measuring signals resulting from the contact – even from very fast contact situations - normally include frequencies up to 100 Hz. The measuring frequency should therefore amount to at least 1 kHz. The measuring signals have to be filtered by means of a Butterworth low-pass filter of a limiting frequency of 100 Hz (at 3 dB) and a slope of 24 dB/octave.

In the majority of cases, clamping situations of the body regions hands and lower arms are decisive for the design of the system, the tools and workpieces as well as for the safety parameter setting (Table 1 quasi-static contact). Due to the edges of the tools and workpieces, the clamping pressure is usually the decisive factor.

In some cases, it may be necessary to measure dynamic values, e. g. if the risk assessment shows that even bumping of robot system parts against the body in the free space is possible.

In order to achieve reproducible measuring results, the measuring device has to be fixed for this case as well. An example of a measuring arrangement is shown in Figure 7. Difference is made between two contact situations:

a) Clamping, e.g. in the area of a device

The permanently occurring clamping forces and pressures are evaluated. Depending on the clamping situation, additional peaks may occur (see figure 7 bottom left) They must not exceed the limit values for short-term applications (see Table A.2).

b) Bumping in free space

The measured force or pressure maximum is evaluated. Continuously occurring clamping forces and clamping pressures need not be expected due to the dodge reaction.

Technical documentation or marking	May remain with the manu-facturer (system integrator)	To be supplied with the robot system or indicated on the robot system
EC Declaration of conformity for the robot system		X
Operating instructions for the robot system		X
Technical documentation according to Directive 2006/42/EC Annex VII	X	
Risk assessment	X	
Type plate with name and address of system integrator (type plate of robot manufacturer not sufficient, example see Figure 8)		X
CE mark		X
Machine designation, e. g. „Collaborative robot system“		X
Year of construction		X
Series or type designation		X
Special additional information acc. to ISO TS 15066 clause 7, e. g. biomechanical limit values (force, pressure) for individual contact situation		X

Table 2: Minimum markings and documents to be supplied

It would be desirable for the future, if simulation tools of the robot manufacturers enable the phase out of measurements. For the time being, such simulation tools are not yet available.

7 Documentation and marking of equipment

Collaborative robot systems fall within the scope of the EC Machinery Directive. According to the legal provisions, at least the technical documentation or the markings mentioned in Table 2 have to be provided.

For collaborative robot systems, further documents have to be provided in particular. According to ISO TS 15066, clause 7, the biomechanical limit values (force, pressure) for the relevant contact situation to be expected have to be indicated. This information has to be supplied to the customer together with the robot system.

In the scope of the operating instructions even those protective measures have to be indicated which have to be implemented as instructions to the operators by the user. For this, it is very important that the instructions are reasonable and understandable to the operators and can be applied. Reference points are:

- sufficient lighting of the work area, particularly of possible contact areas
- stability at the workplace, e. g. slip-resistant floor, suitable standing aid
- simple procedures for stopping, restarting and retracting the robot system, e. g. in emergency situations
- prevention of attention restrictions, e. g. avoiding disturbances by adjoining workplaces due to noise
- employment of operators with sufficient qualification and experience.
- prevention of presence of a third person in the collaborative area, e. g. access only under supervision
- design of work processes and protective measures with regard to the avoidance of operator mistakes, e. g. clear path design, ergonomic workplace design
- regular and special purpose inspections, e. g. remeasurement of biomechanical limit values after retrofitting or program change.
- summarized codes of behaviour durably and clearly visible on the system (operating instructions)
- information on measures for risk assessment on the workplace in conjunction with possible contact situations and the operator’s state of health.

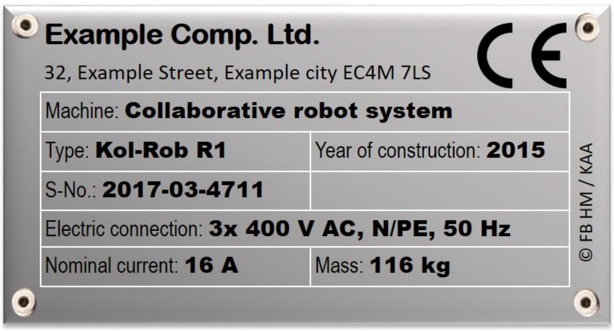


Figure 8: Example type plate with CE mark

8 Risk assessment at the workplace and recurrent inspections

According to the Ordinance on Industrial Safety and Health [8], risk assessments at the workplace have to be carried out for workplaces at collaborative robot systems and protective measures have to be specified. The risk assessments at the workplace have to be documented. Particular hazards which are different from those of other machine workplaces are, e. g.:

- being clamped or missing possibility to free oneself
- presence of another person
- psychical hazard

The Ordinance on Industrial Safety and Health also requires regular inspections to be carried out on the collaborative robot system. The inspections should at least include visual inspections and function tests and should be carried out in yearly intervals. In the course of the use of the collaborative robot system, the biomechanical load values may change, e.g. due to

- modified application, e.g. due to reconstruction
- wear of joints and brakes
- particular incidents (accidents, crashes, repair)
- program change
- parts change

Inspections of the biomechanical load values have to be included in the measures. In case of wear or repair, internal system tests or reference measurements of biomechanical load values can be sufficient, depending on the type of robot system.

9 Summary and limits of application

This DGUV-Information is based on expert knowledge and insights from accidents gathered by the expert committee woodworking and metalworking, subcommittee machinery, systems and automation of Deutsche Gesetzliche Unfallversicherung DGUV.

Presently, there exist only a few practical instruction guidelines [9, 10]. The aim of this expert information is to support manufacturers and users, system integrators and certifiers with the development, construction, certification and assessment of safe collaborative robot systems according to the requirements of EC Directives and harmonized standards.

This DGUV-Information only covers industrial robot systems of the collaborative type (Power and Force Limiting). Industrial robot systems of other types as well as household robots, service robots, medical robots, miniature robots and similar are not dealt with.

A further DGUV-Information for the risk assessment at collaborative robot systems is envisaged.

The provisions according to individual laws and regulations remain unaffected by this DGUV-Information. The requirements of the legal regulations apply in full.

In order to get complete information, it is necessary to read the relevant regulation texts and the current standards.

The expert committee woodworking and metalworking is composed of representatives of the German Social Accident Insurance Institutions, federal authorities, social partners, manufacturers and users.

This DGUV-Information replaces the same-titled version, published as draft 04/2017. Further DGUV-Information or information sheets of the expert committee woodworking and metalworking are available for download on the internet. [11].

As to the aims of the DGUV-Information, refer to DGUV-Information FB HM-001 „Aims of the DGUV-Information, published by the expert committee woodworking and metalworking“.

Bibliography:

[1] Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast**)** - Official Journal of the European Union L 157/24

[2] DIN EN ISO 10218-1 Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robots, 2012-01, Beuth Verlag, Berlin

[3] DIN EN ISO 10218-2 Robots and robotic devices - Safety requirements for industrial robots - Part 2: Robot systems and integration, 2012-03, Beuth-Verlag, Berlin

[4] DGUV Information 209-074 “Industrial robots” (DGUV). Issue January 2015.

[5] ISO TS 15066: 2016-02 Robots and robotic devices - Collaborative robots. Date of issue: 2016-02. Beuth-Verlag, Berlin

[6] DIN EN ISO 13849-1 Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design, 2008-12, Beuth-Verlag

[7] Scientific final report to project FP-0317: „Collaborative robots – Determination of pain sensitivity at the human-machine interface“ - University Medical Center - Institute of Occupational, Social and Environmental Medicine, Obere Zahlbacher Straße 67, 55131 Mainz

[8] Regulation on safety and health protection in providing work equipment (Ordinance on Industrial Safety and Health– BetrSichV) of 3 February 2015 (BGBl. I S. 49), last amended by article 1 of the regulation of 13 July 2015 (BGBl. I S. 1187).

[9] BG/IFA- recommendations for risk assessment at the workplace according to Machinery Directive - Design of workplaces with collaborative robots. U 001/2009 October 2009

[10] VDMA-Position paper "Safety in Human-Robot Collaboration" VDMA Robotics and automation 2014.

[11] Internet: www.dguv.de/fb-holzundmetall publications or www.bghm.de Webcode: <626>

[12] Yamada, Suita, Ikeda, Sugimoto, Miura, Nakamura: Evaluation of Pain tolerance based on a biomechanical method for Human-Robot Coexistence. Transactions of the Japan Society of Mechanical Engineers. 1997. Page 2814-1819

[13] D. Mewes, F. Mauser: Safeguarding Crushing Points by limitation of Forces. International Journal of Occupational Safety and Ergonomics (Jose), Vol. 9, No. 2, 177-191

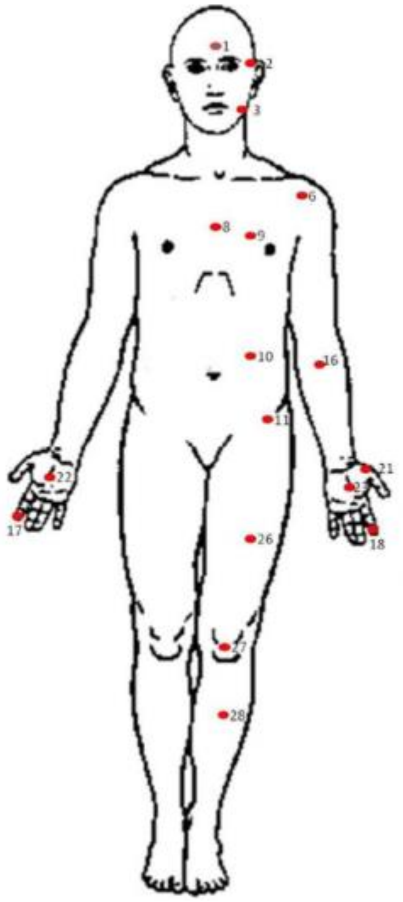
Picture credits:

The pictures mentioned in this DGUV-Information of the expert committee woodworking and metalworking (FB HM) have been kindly provided by:

Figure 1 - 8: FB HM, SG MAF

Publisher:

Fachbereich Holz und Metall der DGUV
Sachgebiet Maschinen, Anlagen und Fertigungsautomation
c/o Berufsgenossenschaft Holz und Metall
Postfach 37 80
55027 Mainz
Germany

Front side of the body		Specific localization	Region of the body
	1	middle of forehead	skull/forehead
	2	temple	skull/forehead
	3	masticatory muscle	face
	6	shoulder joint	back/shoulders
	8	sternum	chest
	9	pectoral muscle	chest
	10	abdominal muscle	abdomen
	11	pelvic bone	pelvis
	16	arm nerve	upper arms/elbow joints
	17	forefinger pad d	hands/fingers
	18	forefinger pad nd	hands/fingers
	21	thenar eminence	hands/fingers
	22	palm d	hands/fingers
	23	palm nd	hands/fingers
	26	thigh muscle	thighs/knees
	27	kneecap	thighs/knees
	28	shin	lower legs
	d	dominant side of the body	
	nd	non-dominant side of the body	

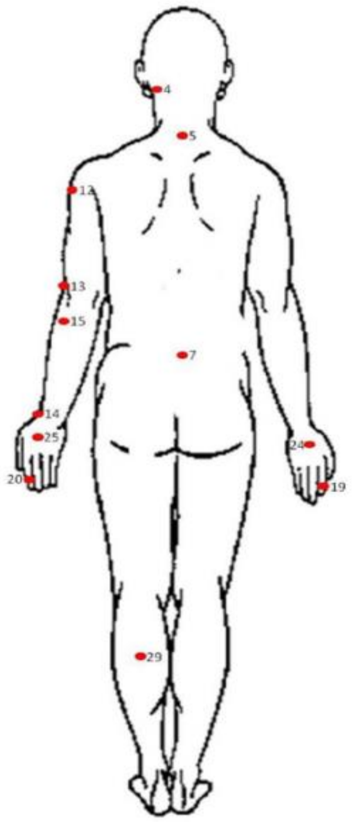
Back side of the body		Specific localization	Region of the body
	4	neck muscle	neck (sides/nape)
	5	seventh neck vertebra	neck (sides/nape)
	7	fifth lumbar vertebra	back/shoulders
	12	deltoid muscle	upper arms/elbow joints
	13	humerus	upper arms/ellbow joints
	14	radial bone	lower arms/wrist joints
	15	forearm muscle	lower arms/wrist joints
	19	forefinger end joint d	hands/fingers
	20	forefinger end joint nd	hands/fingers
	24	back of the hand d	hands/fingers
	25	back of the hand nd	hands/fingers
	29	calf muscle	lower legs
	d	dominant side of the body	
	nd	non-dominant side of the body	

Table A.1: **body model**

Body localizations			Quasi-static contact (clamping)		Transient contact (free impact)	
Specific localization		Body region	Peak pressure p_S [N/cm²] (note 1)	Force F_S [N] (note 2)	Peak pressure P_T multiplier (note 3)	Force F_T multiplier (note 3)
1	middle of forehead	skull and forehead	130	130	none	none
2	temple	critical zone	110			
3	masticatory muscle	face	110	65		
4	neck muscle	neck	140	150	2	2
5	seventh neck vertebra		210			
6	shoulder joint	back and shoulders	160	210		
7	fifth lumbar vertebra		210			
8	sternum	chest	120	140		
9	pectoral muscle		170			
10	abdominal muscle	abdomen	140	110		
11	pelvic bone	pelvis	210	180		
12	deltoid muscle	upper arms and elbow joints	190	150		
13	humerus		220			
14	radial bone	lower arms and wrist joints	190	160		
15	forearm muscle		180			
16	arm nerve		180			
17	forefinger pad d	hands and fingers	300	140		
18	forefinger pad nd		270			
19	forefinger end joint d		280			
20	forefinger end joint nd		220			
21	thenar eminence		200			
22	palm d		260			
23	palm nd		260			
24	back of the hand d		200			
25	back of the hand nd		190			
26	thigh muscle	thighs and knees	250	220		
27	kneecap		220			
28	middle of shin	lower legs	220	130		
29	calf muscle		210			

Table A.2 — biomechanical limit values

Note 1:
The values indicated for the peak pressure have been determined in the scope of a study carried out by an independent institution [7]. 100 subjects from industry and public were experimentally examined. The indicated limit values are thresholds of pain occurrence, i.e. the point of perception threshold when a perceived pressure sense turns into a beginning pain. The indicated peak pressures correspond to the third quartile which has been determined in the study. The study applied devices which had been particularly developed for that purpose. The study was commissioned by Deutsche Gesetzliche Unfallversicherung (DGUV) including consultative cooperation with ISO TC 184 SC 2 WG 3 and DIN NAM 60-30-02-AA.

Note 2:
The values indicated for the force have been determined in the scope of a literature study which was carried out by the Institut für Arbeitsschutz for this purpose [8]. 180 literature sources have been evaluated. The indicated limit values refer to thresholds of the occurrence of injuries below AIS 1. According to previous experience, the limit values are considered to be sufficiently conservative. Further research as to the specification of force limit values is in preparation.

Note 3:
The limit values for transient contact have to be used as multiplier (multiplication of the values for quasi-static contact). They are derived from the literature sources [12, 13]. According to literature references, multipliers of at least two are indicated, however, as a rule, greater than two. The indicated limit values are considered to be sufficiently conservative. Further research for specifying transient biomechanical limit values is in preparation.

Note 4
The biomechanical limit values according to Table A.2 have been taken over in ISO TS 15066.